2011

Carbon dioxide fluxes in corn–soybean rotation in the midwestern U.S.: Inter- and intra-annual variations, and biophysical controls

Guillermo Hernandez-Ramirez
Canterbury Agriculture and Science Centre, Guillermo.Hernandez@plantandfood.co.nz

Jerry L. Hatfield
USDA-ARS, jerry.hatfield@ars.usda.gov

Timothy B. Parkin
USDA-ARS

Thomas J. Sauer
USDA-ARS

John H. Prueger
USDA-ARS

Agricultural and Forest Meteorology 151 (2011) 1831–1842

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Carbon dioxide fluxes in corn–soybean rotation in the midwestern U.S.: Inter- and intra-annual variations, and biophysical controls

Guillermo Hernandez-Ramirez[a,*], Jerry L. Hatfield[b], Timothy B. Parkin[b], Thomas J. Sauer[b], John H. Prueger[b]

[a] New Zealand Institute for Plant and Food Research, Canterbury Agriculture and Science Centre, Private Bag 4704, Christchurch, New Zealand
[b] USDA-ARS, National Laboratory for Agriculture and the Environment, Ames, IA 50011-3120, USA

ARTICLE INFO

Article history:
Received 6 May 2011
Received in revised form 25 July 2011
Accepted 26 July 2011

Keywords:
Temporal variability
Hysteresis
Available light
Photosynthetically active radiation
Air temperature

ABSTRACT

Quantifying carbon dioxide (CO_2) fluxes in terrestrial ecosystems is critical for better understanding of global carbon cycling and observed changes in climate. This study examined year-round temporal variations of CO_2 fluxes in two biennial crop rotations during 4 year of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production. We monitored CO_2 fluxes using eddy-covariance (EC) and soil chambers in adjacent production fields near Ames, Iowa. Under the non-limiting soil water availability conditions predominant in these fields, diel and seasonal variations of CO_2 fluxes were mostly controlled by ambient temperature and available light. Air temperature explained up to 81% of the variability of soil respiratory losses during fallow periods. In contrast, with full-developed canopies, available light was the main driver of daytime CO_2 uptake for both crops. Furthermore, a combined additive effect of both available light and temperature on enhanced CO_2 uptake was identified only for corn. Moreover, diurnal hysteresis of net CO_2 uptake with available light was also found for both crops with consistently greater CO_2 uptake in the mornings than afternoons perhaps primarily owing to delay in peak of soil respiration relative to the time of maximum plant photosynthesis. Annual cumulative CO_2 exchange was mainly determined by crop species with consistently greater net uptake for corn and near neutral exchange for soybean (-466 ± 38 and $-13 \pm 39\,\mathrm{g\,C\,m^{-2}\,year^{-1}}$). Concomitantly, within growing seasons, CO_2 sink periods were approximately 106 days for corn and 90 days for soybean, and peak rates of CO_2 uptake were roughly 1.7-fold higher for corn than soybean. Apparent changes in soil organic carbon estimated after accounting for grain carbon removal suggested soil carbon depletion following soybean years and neutral carbon balance for corn. Overall, results suggest changes in land use and cropping systems have a substantial impact on dynamics of CO_2 exchange.

1. Introduction

Current global climate change is evidenced by ongoing increases in ambient temperature, rising sea level, and decreases in snow cover worldwide (IPCC, 2007). These accelerated processes have been mostly attributed to progressively increasing concentration of CO_2 in the atmosphere (IPCC, 2007; Graßl, 2009). Relative to the preindustrial level, the global atmospheric concentration of CO_2 has already increased by 35% (from approximately 280 to 379 $\mu\mathrm{L\,L^{-1}}$); this newly-added atmospheric CO_2 has been mainly sourced from fossil fuel combustion and land-use change, and it is considered to contribute 77% of the current global warming effect (Houghton, 1999; IPCC, 2007). Major science efforts are now focusing on identifying and developing suitable land-management strategies to effectively mitigate or decelerate these detrimental global environmental effects (Suyker et al., 2004; Johnson et al., 2005; Russell et al., 2005; Hutchinson et al., 2007). Both extensive quantification of CO_2 fluxes in diverse terrestrial ecosystems and enhanced understanding of their controlling environmental factors (Law et al., 2002; Griffis et al., 2003) are needed to select effective management strategies to enhance carbon sequestration (Baker and Griffis, 2005; Verma et al., 2005; Glenn et al., 2010) as well as for improving prediction ability of terrestrial CO_2 fluxes when modeling future climate scenarios (Grant et al., 2007; Migliavacca et al., 2011).

Several studies have indicated the key controlling roles of available light, ambient temperature, and rainfall patterns on CO_2 fluxes (Law et al., 2002; Griffis et al., 2003; Pingintha et al., 2010; Reverter et al., 2010). In general, it has been established that while increased available light enhances ecosystem CO_2 uptake within growing seasons via plant photosynthetic activity (Griffis et al., 2003; Suyker

* Corresponding author.
E-mail address: Guillermo.Hernandez@plantandfood.co.nz (G. Hernandez-Ramirez).

0168-1923/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2011.07.017

et al., 2004; Pingintha et al., 2010; Glenn et al., 2010), increased ambient temperature typically favors ecosystem respiration (Law et al., 2002; Griffis et al., 2003; Suyker et al., 2004; Brown et al., 2009), and variations in soil water content as a function of rainfall can in general result in increased CO_2 emission during non-growing periods (Granier et al., 2007; Pereira et al., 2007; Reverter et al., 2010) or mixed effects during growing seasons (Verma et al., 2005; Granier et al., 2007; Pingintha et al., 2010; Reverter et al., 2010). However, these environmental control factors have typically been examined separately as single factors, and hence, their additive or interacting effects are not well documented in the existing literature. After studying a native grassland ecosystem, Saito et al. (2009) reported a combined effect of increases in both available light and soil temperature (i.e., >8 °C) on increased CO_2 uptake. Nonetheless, such multivariate relationships have not been examined in annual cropping systems. Indeed, to date, the majority of the studies about environmental controls on ecosystem CO_2 exchange have been conducted in forest (Law et al., 2002; Griffis et al., 2003; Granier et al., 2007; Migliavacca et al., 2011) and grassland (Pereira et al., 2007; Brown et al., 2009; Saito et al., 2009; Unger et al., 2010) ecosystems, whereas cropland systems (Suyker et al., 2004; Pingintha et al., 2010) have a disproportionally minor representation of these studies relative to their wide surface cover distribution worldwide. The effects of environmental controls on CO_2 exchange could vary to a great degree between croplands and other ecosystems due to inherent differences in plant phenologies and canopy structures, and durations of the fallow and growing periods as well as the application of management practices in cropping systems. Thus, information available regarding environmental controls on CO_2 exchange over cropland systems is lacking, limited, and dispersed.

The two predominant annual crop species in the Midwestern U.S. region are corn and soybean, covering approximately 75% of the land surface (Hatfield et al., 2007). To date, a few field studies have examined the long-term CO_2 exchange over croplands within this region in response to varying management factors (Baker and Griffis, 2005; Hollinger et al., 2005; Verma et al., 2005). It has been observed that recent management transition to conservation tillage practices apparently had no significant effect on annual CO_2 exchange over corn–soybean rotations (Baker and Griffis, 2005; Verma et al., 2005). Similarly, when contrasting annual CO_2 exchange of corn–soybean rotations under rainfed versus irrigated systems, little response to management has also been detected (Verma et al., 2005). These existing multi-year studies generally did not simultaneously compare side-by-side the two crop species (i.e., corn and soybean) in all studied years, but typically evaluated corn and soybean cultivation only in alternative years as part of a single site biennial rotation system. To measure CO_2 fluxes over the two crops simultaneously during multiple years would prevent introducing confounding effects of inter-annual climate variations in the CO_2 exchange results. Furthermore, ecosystem carbon balances reported in these existing studies fluctuated from net source to neutral outcomes, in part, demonstrating that CO_2 exchange over cropland is highly variable and dynamic. Therefore, additional data collected under a broad variety of edaphic and climatic conditions can help to resolve these carbon sink-source uncertainties at the ecosystem level. More data are also needed to enhance flux quantification across the existing regional gradients of precipitation (increasing west to east) and ambient temperature (increasing north to south) in the Midwestern U.S. as well as to unravel the high temporal variations of ecosystem CO_2 fluxes. To understand the temporal dynamics of these patterns in response to both environmental factors and different land-management is also critical for better interpretation of CO_2 fluxes in agricultural fields and at global terrestrial scales. Thus, the objectives of this study were to quantify long-term temporal variations of CO_2 fluxes in corn and soybean fields, and to examine the biophysical controls on these fluxes in the Midwestern U.S. This study also addressed specific research questions including inter- and intra-annual variations of CO_2 fluxes over plant canopies and under fallow conditions; assessment of CO_2 exchange at regional footprint scale level by intercomparison between CO_2 exchange measured at 10 m height above the ground vs. directly over canopy or fallow surfaces; transient effects of crop phenological developments and tillage operations on CO_2 fluxes; dependency of CO_2 fluxes on available light, ambient temperatures, and rainfall; and examination of hysteresis response of ecosystem CO_2 uptake with available light.

2. Materials and methods

2.1. Site description and agronomic management

This study was conducted near Ames, Iowa (41.967° N, 93.695° W, 315 m elevation) from 2004 through 2007. Soil series in the field are Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) with terrain slopes of 0–3%.

Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] were grown in biennial rotation in two adjacent fields with both crops in any given year. Corn–soybean rotation is the dominant cropping system within the geographic region of this study (Hatfield et al., 2007). The assessed, large-scale, commercial production fields (≥23 ha) in our study were typically planted in early May and harvested for grain in late October. Crop residues remained in these fields following harvest operations. In close agreement with the actual planting to harvest periods within every year, the growing season period in this study was defined as 1 May through 31 October. Corn and soybean population densities were approximately 72 000 and 350 000 plant ha^{-1}, respectively. Tillage operations included fall chisel plowing only in the corn field and one pass of field cultivator in the spring prior to planting of both crops. After soybean harvest, nitrogen fertilizer was injected at a rate of 168 kg ammonia-N ha^{-1} in the fall in preparation for corn planting in the following spring. These fields are drained with subsurface tile lines (≈1 m depth). Typical dates of growth stages R1 and R5 for soybean were on 9 July and 11 August, respectively, while R1 for corn was on 18 July. Peak canopy heights were 294 cm for corn and 93 cm for soybean. Leaf area index for corn at growth stage R1 measured using a LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences Inc., Lincoln, NE) was typically 5.9 $m^2 m^{-2}$. Also, in these same fields of our study, Sauer et al. (2007) quantified peak leaf area index for soybean of typically 5.8 $m^2 m^{-2}$.

2.2. Field measurements and data calculations

A permanent weather station was deployed within 1 km from the study site over a grassed area for continuous measurements of vapor pressure deficit (VPD) and air temperature (Vaisala HMP45c, Campbell Scientific Inc., Logan, UT), solar radiation and incident photosynthetically active radiation (PAR) densities (LI-200 pyranometer, LI-COR Biosciences Inc.), and cumulative precipitation (TR-525 Rain Gauge, Texas Electronics Inc., Dallas, TX.). Data were computed and recorded hourly using a CR1000 datalogger (Campbell Scientific Inc.).

2.2.1. Eddy-covariance instrumentation

Eddy-covariance (EC) flux instrumentation were positioned 1.6 m above the soil surface (or 1 m above canopy height if canopy height >0.6 m) in each of the two cropped fields. Similar to Hernandez-Ramirez et al. (2011c), these EC units consisted of a fast-response water vapor and CO_2 density open-path infrared gas analyzer (IRGA; LI-7500, LICOR Biosciences Inc.) and a three-dimensional sonic anemometer (CSAT, Campbell Scientific Inc.) oriented to the prevailing wind direction (i.e., to the south). Separation distance between gas analyzer and sonic anemometer sensors was 0.1 m. Ancillary measurements in each flux station included air temperature and humidity, and soil water content. An air temperature and humidity sensor (HMP-35, Vaisala Inc., Woburn, MA) was placed within 0.2 m above the EC sensors. Soil water content in the top 0.1 m at each site was measured with Hydra Probe (Stevens Water Monitoring Systems, Portland, OR) deployed at the interrow (if crop was present). Signals from all EC instrumentation were recorded at rates of 10 Hz, and 15-min averages were stored in CR5000 dataloggers (Campbell Scientific Inc.). All instrumentation at the site was powered using twelve-volt DC batteries supplemented with arrays of solar panels and/or wind generator as needed.

A third EC unit using the identical instrumentation as the ECs mentioned above was deployed at 10 m above the ground level on a tower located in the boundary between the two cropped fields. This 10 m-high EC system was installed with the aim of providing a regional-scale footprint assessment of CO_2 fluxes over this agricultural landscape. This 10 m-high EC data was available only for calendar years 2006 and 2007.

2.2.2. Eddy-covariance data procedures

Calculations for EC data were carried out in three sequential steps including corrections, quality control, and gap-filling. Measured CO_2 fluxes were corrected for air density fluctuations following the Webb–Pearman–Leuning algorithm (Webb et al., 1980). Our times series CO_2 concentration data was not corrected for the effects of local heating by the open-path IRGA sensor which can particularly occur during cold periods (Grelle and Burba, 2007; Amiro, 2010). We recognize that this self-heating correction is increasingly being applied in CO_2 exchange studies (Reverter et al., 2011), and therefore, as describe below, we used a regression model developed by Reverter et al. (2011) to attain a quantitative estimate of its magnitude in our results of annual cumulative CO_2 fluxes and apparent carbon balance.

Quality control consisted of a rigorous data screening protocol. Data were rejected if wind direction was opposite to the orientation of EC system, and also if the friction velocity was below a pre-selected threshold of 0.1 m s^{-1} after Baker and Griffis (2005). Data was also screened for anomalous values outside a pre-selected range [−1.36 to 2.73 mg CO_2-C m^{-2} s^{-1}; with sign convention defined as flux values are positive when CO_2 is transported away from the surface (emission)]. Instrument malfunctioning and power failure also caused data losses. Additionally, any data collected by the EC systems during rainy periods was systematically rejected because of sensor malfunction during these events. Rainy periods encompassed 2.2% of the time across the 8 site-years of our study. All these constraints produced a total amount of missing EC CO_2 data of 31% across the 10 site-years.

With the exception of rainy periods, intervals of missing data were gap filled using an iterative interpolation technique. Gap filling of our missing data allowed the estimation of cumulative seasonal and annual totals of CO_2 flux densities. This gap filling procedure for missing data was run using an inverse weighting time average calculation based on nearest neighbours as Hernandez-Ramirez et al. (2009b, 2010). Briefly, the gap-filling algorithm was performed in three sequential steps: gap filling of 15-min missing data, daily mean estimation, and gap filling of missing daily data. Gap-filled 15-min missing data was performed as a one-dimensional moving frame with a maximum of 24 neighbours in the time course and centered in the missing data period of interest. Following a conservative approach, the outcome from gap-filled 15-min data calculation was accepted and incorporated into the data set only if at least 8 neighbour data values were presented within the moving frame. Gap-filled data sets (original 15-min data along with valid gap-filled 15-min data for missing periods) were used to calculate daily mean of CO_2 flux density. Nonetheless, for quality control purposes, these daily means of CO_2 flux density were rejected if more than 20% of available 15-min data were still missing for a given day after applying the gap-filling technique. Using these screened daily means, gap-filling of daily missing data was carried out as a centered moving frame of at least 4 and maximum 48 neighbour values. The combined data set included 69% of original 15-min data, 20% gap-filled derived 15-min data, and 11% of gap-filled derived daily data.

As it is convention for the EC method, energy balance for our data sets has been previously examined. In related work, Hernandez-Ramirez et al. (2010) observed annual energy balance closures of 0.87 for corn and 0.81 for soybean fields. As discussed by Hernandez-Ramirez et al. (2010), increased advective losses over relatively smoother surfaces (i.e., soybean canopy), turbulent transport by large-scale eddies (low frequency), as well as other minor energy fluxes and storage terms (e.g., photosynthesis, air and canopy storage) could contribute to explain these observed results of energy balance closure in these fields.

2.2.3. Automatic soil chamber instrumentation

To assess soil CO_2 flux under fallow conditions, two stainless steel chambers were deployed per field site during the growing season of 2004. Chamber dimensions were 0.60 m by 0.60 m and 0.30 m tall, and the chambers were inserted 15 cm deep in the soil for a chamber headspace volume of 54 L. The area within a 2-m distance from the chambers was kept free from any crop plants or weeds. Chambers were removed to allow field operations including tillage and repositioned within a few hours after the field operations. As described in Parkin and Kaspar (2003), the chambers had a linear motor for automatically closing and opening the chamber cover. Each chamber was equipped with a vent port to allow pressure equilibration with the atmosphere. A small fan was installed inside each chamber to mix the air (6.7 L s^{-1}) during the CO_2 flux measurements. Flux measurements were done at hourly intervals by closing the chambers for 6 min and quantifying headspace CO_2 concentrations every minute. These six CO_2 concentrations were used to estimate a flux value as a point measurement. Headspace CO_2 concentration were measured by pumping a headspace gas sample through an infrared gas analyzer (IRGA) (LI-800 GasHound, LICOR Biosciences Inc.) and out to the atmosphere at a flow rate of 0.0108 L s^{-1}. Dataloggers (CR21X, Campbell Scientific Inc.) were used to control the chamber automation and to calculate and store hourly flux data.

2.2.4. Chamber and eddy-covariance data analyses

Chamber flux estimations were done by fitting CO_2 concentration versus time data to the curvilinear algorithm proposed by Hutchinson and Mosier (1981). Flux values were corrected for the CO_2 exchange between the chamber headspace and the atmosphere through both the vent port and the IRGA pump.

To examine the dependency of soil CO_2 fluxes on temperature under fallow conditions, acquired EC (during fallow periods) and chamber data sets were fitted to both linear regressions and Q_{10} relationships. Coefficients of determination (R^2) were used as criterion for best model selection. Similar to Parkin and Kaspar (2003) and Hernandez-Ramirez et al. (2009b), Q_{10} parameters were derived using the nonlinear Arrhenius equation with a basal CO_2 flux set at a temperature of 283 K.

Due to lack of constant variance of CO_2 fluxes data, non-parametric Kruskal–Wallis one way analyses of variance on ranks were run to compare annual cumulative and seasonal components

Table 1
Net ecosystem exchange of carbon dioxide (CO_2) over a corn–soybean rotation in Iowa using eddy-covariance (EC) method and accumulated on both annual and seasonal bases.

Year or statistic	Cumulative CO_2–C flux[a]			
	Annual	Seasonal components		
	1 January through 31 December	1 January through 30 April	1 May through 31 October (growing season)	1 November through 31 December
	g C m^{-2}			
Corn field				
2004	−534	73	−653	46
2005	−473	62	−584	49
2006	−497	117	−657	43
2007	−360	78	−456	18
Mean	−466	83	−588	39
SE[b]	38	12	47	7
Soybean field				
2004	−122	89	−251	40
2005	4	64	−78	18
2006	5	89	−112	28
2007	62	71	−33	24
Mean	−13	78	−119	28
SE[b]	39	6	47	5
10 m-high EC[c]				
2006	−279	104	−413	30
2007	−142	86	−247	19
Mean	−211	95	−330	25
SE[b]	69	9	83	6

[a] Sign convention: flux values are positive when CO_2 is transported away from the surface (emission).
[b] Standard error of the mean.
[c] Corresponds to an EC deployed on a 10 m-high tower for regional-scale footprint assessment of CO_2 fluxes located in the boundary between the two assessed, cultivated fields (i.e., corn and soybean).

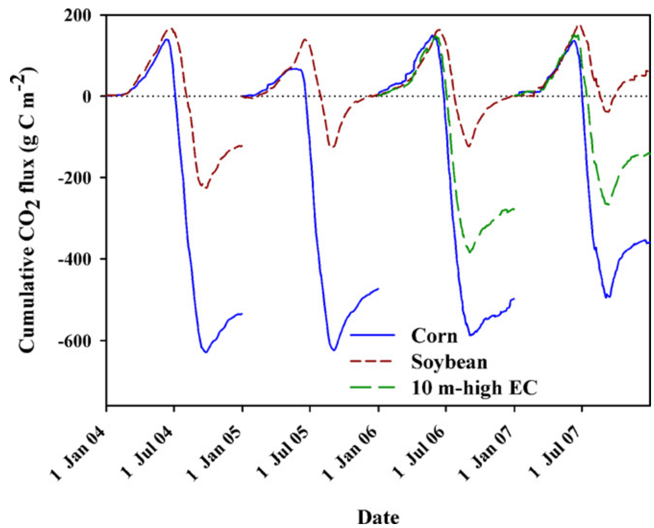

Fig. 1. Net ecosystem exchange of carbon dioxide (CO_2) over a corn–soybean rotation in Iowa using the eddy-covariance (EC) method. The '10 m-high' values corresponds to an EC deployed at 10 m above ground level with the purpose of regional-scale footprint quantification of CO_2 fluxes located in the boundary between the two assessed, cultivated fields (i.e., corn and soybean). Shown values were accumulated on daily-step basis within each calendar year. The 10 m-high EC data were available only for calendar years 2006 and 2007.

of CO_2 fluxes for the 10 m-high tower vs. the simple average of corn and soybean fields where the measurement years were used as replicates. Linear least square regressions were fitted to the CO_2 fluxes data as a function of PAR and/or ambient temperature. Prior to parametric model development, response data (CO_2 fluxes) were assessed for normality and constant variance by Bartlett and Shapiro–Wilk tests, respectively. Due to a lack of both normality and constant variance, CO_2 fluxes data were offset to positive values and transformed by natural logarithm or square root as needed to fulfill the assumptions required for model development.

3. Results and discussion

3.1. Net ecosystem exchange of CO_2: Inter-annual variations and crop effects

Within the assessed corn–soybean rotations, all corn years consistently showed net uptakes of CO_2 (ranging from −534 to −360 g C m^{-2} year^{-1}), whereas soybean exhibited annual cumulative CO_2 exchanges near neutral values (−122 to 62 g C m^{-2} year^{-1}, Table 1; Fig. 1). These observed quantities are in general agreement with previous CO_2 exchange studies conducted in corn and soybean fields in central North America (compiled in Table 2). Moreover, certain variations in CO_2 exchange amongst these existing reports can be in part explained by natural gradients of both temperature and precipitation across this geographic region. Study sites of Baker and Griffis (2005) (Minnesota) and Glenn et al. (2010) (Manitoba) located to the north of our measurement site typically showed much lower corn CO_2 uptake than our results which can in part be attributed to gradual decreases in ambient temperature toward the northern latitudes. Likewise, when comparing rainfed corn fields, an increasing precipitation gradient from west to east within the Midwestern U.S. could have caused annual CO_2 uptake to be greater in Illinois (Hollinger et al., 2005) and lower in Nebraska (Verma et al., 2005) than in our measurement location in Iowa mainly due to associated variations in net primary productivity.

Moderate weather variations amongst the four years of our study could partly explain the differences in measured magnitudes of annual CO_2 exchange across the assessed years. Both the highest annual net CO_2 uptake for corn and the only net uptake value for soybean took place in 2004 (Table 1; Fig. 1). Concurrently, the growing season 2004 (May through October) exhibited the highest rainfall and lowest temperature compared to the other three years of our study (Table 3). Because summers in temperate regions are typically warm, these comparatively slightly colder-wetter conditions during 2004 could have decreased plant and soil respiration rates in relative terms while sustaining adequate conditions for plant growth, photosynthetic activity, and biomass accumulation (Taiz and Zeiger, 2002). In contrast, comparatively warmer-wetter conditions during the growing season of 2007 could have in part caused the lowest CO_2 uptakes for both corn and soybean crops across the four assessed years (−456 and −33 g C m^{-2} during growing season 2007, respectively; Table 3). In effect, warmer-wetter conditions within the growing season of 2007 could have specifically favored respiratory processes in both soil and plant components of these cropping systems where existing subsurface drainage networks typically remove the excess of soil water. The direct dependency of soil respiration on both temperature and soil water contents have been extensively demonstrated in previous field and incubation studies focusing on only the soil component of cropping systems (Parkin and Kaspar, 2003; Davidson et al., 2006).

Because EC measurements over crop canopies integrate the net effects of plant photosynthesis as well as plant and soil respiration processes, subtraction of carbon exported via harvested grain from our EC-measured annual CO_2 exchange (Table 1; Fig. 1) could be interpreted as apparent annual changes of soil carbon. Combine-harvested grain productivities (Mg dry matter ha^{-1} year^{-1}) in the assessed commercial fields were typically 11.8 for corn and 3.1 for

Table 2
Data compilation for annual cumulative net ecosystem exchange of carbon dioxide (CO_2) from micrometeorological measurements done over croplands and grasslands in North America.

Land use	Management	Site location	CO_2 flux ($g\,C\,m^{-2}\,year^{-1}$)[a]	Precipitation ($mm\,year^{-1}$)[b]	Temperature (°C)[b]	Site-years	Reference
Corn phase of a corn–soybean rotation	Conventional	Ames, IA, US	−466 (−534 to −360)	942 (772–1088)	9.7	4	This study[c]
Soybean phase of a corn–soybean rotation	Conventional	Ames, IA, US	−13 (−122 to 62)	942 (772–1088)	9.7	4	This study[c]
Corn phase of a corn–soybean rotation	Conventional versus strip tillage and cover crop	Rosemount, St. Paul, MN, US	−294 (−290 vs. −300)	956 (946–965)	–	2	Baker and Griffis (2005)[d]
Soybean phase of a corn–soybean rotation	Conventional vs. strip tillage and cover crop	Rosemount, St. Paul, MN, US	−66 (−84 vs. −50)	956 (946–965)	–	2	Baker and Griffis (2005)[d]
Corn phase of a corn–soybean rotation	No tillage	Champaign, IL, US	−576 (−692 to −505)	–	–	3	Hollinger et al. (2005)[c]
Soybean phase of a corn–soybean rotation	No tillage	Champaign, IL, US	−33 (−210 to 104)	–	–	3	Hollinger et al. (2005)[c]
Continuous corn	Irrigation and no tillage	Mead, NE, US	−441 (−517 to −381)	570 (547–607)	11.0	3	Verma et al. (2005)[d]
Corn phase of a corn–soybean rotation	Irrigation and no tillage	Mead, NE, US	−551 (−572 to −529)	586 (556–616)	11.2	2	Verma et al. (2005)[d]
Corn phase of a corn–soybean rotation	No irrigation and no tillage	Mead, NE, US	−454 (−510 to −397)	607 (581–632)	11.4	2	Verma et al. (2005)[d]
Soybean phase of a corn–soybean rotation	Irrigation and no tillage	Mead, NE, US	−48	526	10.6	1	Verma et al. (2005)[d]
Soybean phase of a corn–soybean rotation	No irrigation and no tillage	Mead, NE, US	−18	553	10.7	1	Verma et al. (2005)[d]
Corn	Conventional	Winnipeg, Manitoba, Canada	−72	292	4.7	1	Glenn et al. (2010)[d]

[a] Sign convention: flux values are positive when CO_2 is transported away from the surface (emission). Range of values is presented within parenthesis.
[b] Mean annual values of precipitation and air temperature.
[c] Cumulative values in this study were estimated following calendar year (i.e., 1 January to 31 December).
[d] Cumulative values in this study were estimated following the agricultural cycle beginning at crop planting or seedling emergence (e.g., early May).

soybean (data not shown). Using grain carbon contents ($g\,C\,kg^{-1}$ grain) of 448 for corn and 511 for soybean (Hernandez-Ramirez et al., 2011a), we estimated an annual carbon extraction via grain ($g\,C\,m^{-2}\,year^{-1}$) of 529 ± 30 for corn and 158 ± 7 for soybean. In sum, these estimates suggest near neutral apparent changes in soil carbon following corn years ($63 \pm 68\,g\,C\,m^{-2}\,year^{-1}$), while soybean years resulted in an apparent slow decline in soil carbon ($145 \pm 46\,g\,C\,m^{-2}\,year^{-1}$). Overall, corn–soybean rotation in our study showed an apparent decrease in soil carbon of $104 \pm 57\,g\,C\,m^{-2}\,year^{-1}$. These apparent decreases are quantitatively minimal compared to whole soil profile inventories of organic carbon for both our field site (data not shown) and for another typical Midwestern U.S. soil also cropped to corn–soybean rotation as reported by Hernandez-Ramirez et al. (2009a). On equivalent mass corrected basis, apparent yearly losses of soil carbon in our study represent only 0.44% of the 239 $Mg\,ha^{-1}$ of soil organic carbon measured in our field site during the study period (i.e., soil sampling done in fall 2005 to 1.2 m depth; data not shown), or 0.76% of the 137 $Mg\,ha^{-1}$ of soil organic carbon quantified by Hernandez-Ramirez et al. (2009a) within their 1 m depth soil profiles. It should be noted that our partial carbon balance calculation based on EC-measured CO_2 exchange and grain carbon extraction do not consider several minor components such as leaching losses of dissolved carbon, carbon transport via runoff, and atmospheric carbon deposition (chemical species different than CO_2). As previously pointed out by Baker and Griffis (2005) and Hernandez-Ramirez et al. (2010), it should also be noted that EC method could hypothetically result in systematic underestimate of scalar fluxes including CO_2 exchange mainly due to local advection. Therefore, if this is the case, actual carbon budget estimates would likely shift toward an outcome of neutral carbon balance for our corn–soybean rotations, suggesting this agroecosystem is in

Table 3
Micrometereological factors for the study site during the 4 years of CO_2 flux measurements and 50-year normals. Mean values of air temperature and cumulative precipitation on both annual and growing season bases. Standard errors of the 4-year means are presented.

Year	Precipitation (mm)	Air temperature (°C)
Annual (1 January through 31 December)		
2004	1056	8.9
2005	772	9.9
2006	853	10.4
2007	1088	9.5
4-year mean	942 ± 77	9.7 ± 0.3
50-year normal	843	9.3
Growing season (1 May through 31 October)		
2004	750	17.6
2005	583	19.8
2006	548	17.9
2007	687	19.7
4-year mean	642 ± 46	18.7 ± 0.6
50-year normal	591	19.1

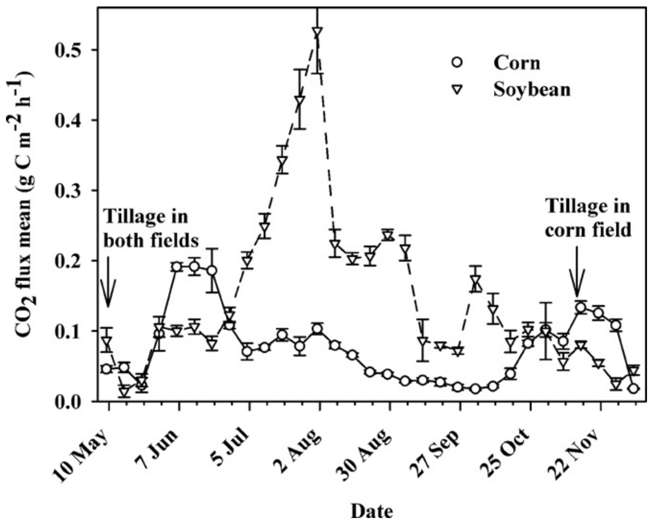

Fig. 2. Temporal dynamics of carbon dioxide (CO_2) fluxes at the soil surface under fallow conditions in corn and soybean fields in Iowa during the growing season of 2004. Two automatic soil chambers were deployed per site. Data shown are 7-day averages derived from hourly measurements (n: 10,962); standard errors of daily averages are also presented. Dates of tillage operations are indicated. Fall tillage was only done in the corn field.

a carbon equilibrium status. Conversely, as mentioned above, the open-path IRGA self-heating correction (Grelle and Burba, 2007) was not systematically applied in our time series data; nevertheless, following a general empirical equation by Reverter et al. (2011) [i.e., CO_2–C correction (g C m^{-2} year^{-1}) = 202–3.4 × mean annual air temperature (°C)] in an attempt to account for this self-heating effect in our annual cumulative results (Table 1) using our mean annual air temperatures (Table 3), it was estimated that annual CO_2 fluxes would be shifted a magnitude of 169 g C m^{-2} year^{-1} toward both enhanced annual net carbon losses for soybean and decreased carbon uptake for corn with corrected 4-year mean fluxes values of 156 and −297 g C m^{-2} year^{-1}, respectively, and hence, estimation of apparent carbon balance for the overall corn–soybean rotation in our study would consequently result in an enlarged decline in soil carbon of 273 g C m^{-2} year^{-1}. This estimated magnitude of yearly soil carbon loss is 2.6 times greater than the carbon balance as calculated above prior applying the self-heating correction. Further research needs to address these various uncertainties in CO_2 exchange measurements and carbon balance.

Existing reports have previously noted the depleting effects of the soybean phase of corn–soybean rotations on soil carbon pools (Russell et al., 2005; Huggins et al., 2007; Hernandez-Ramirez et al., 2009a). Hernandez-Ramirez et al. (2009a) observed a 10% reduction in surface soil organic carbon concentrations following soybean compared to after corn years. These results can in part be attributed to differences in quantity and quality of soybean vs. corn residues with approximately four-fold lesser residue mass and two-fold narrower C/N ratio for soybean residues (Hernandez-Ramirez et al., 2011a). As suggested by Johnson et al. (2005) and Hernandez-Ramirez et al. (2011b), soybean residue quantities represent a low contribution to soil carbon, and in addition, priming effects of N-enriched soybean residue on soil carbon turnover can induce increased microbial respiratory losses of existing soil organic carbon.

3.2. Assessment of CO_2 exchange at the regional footprint level

Several key features can be noted when comparing CO_2 exchange measured at 10 m height above the ground vs. directly over canopy or fallow surfaces during the two assessed years. Annual cumulative CO_2 uptake at the 10 m-high tower (−211 g C m^{-2} year^{-1}) was not different than the simple average of corn and soybean fields (−197 g C m^{-2} year^{-1}) during 2006 and 2007 based on a Kruskal–Wallis one way analysis of variance on ranks (Ps > 0.44) (Table 1; Fig. 1). Likewise, separate statistical analyses by seasonal components also indicate that measurements at 10 m height did not differ than the simple average of the cropped fields. Compared with the simple average of the two cropped fields, CO_2 exchange measured at the 10 m-high tower tended to just 5% higher uptake during the growing seasons (−330 vs. −315 g C m^{-2}) and only 2% higher emission during the fallow periods (November through April) (120 vs. 117 g C m^{-2}). Furthermore, graphical analysis revealed that our cumulative daily CO_2 flux measurements at 10 m height in general followed the averaged temporal patterns of the two cropped fields throughout both 2006 and 2007 (Fig. 1). Overall, these observations support the close agreement between our measurements done at 10 m height for regional-scale CO_2 exchange assessment and within 1.0–1.6 m heights over the two agricultural surfaces. Although our 10 m high EC could have quantified CO_2 fluxes sourced in part from outside the footprint of the corn and soybean fields assessed in this study, this corn–soybean rotation represents the predominant cropping system in the surrounding agricultural landscape within Central Iowa (Hatfield et al., 2007). Few previous studies have assessed CO_2 exchange at a regional footprint level (Soegaard et al., 2003; Jaksic et al., 2006); nevertheless, such assessment had not been previously reported for long-term measurement periods or over heterogeneous agricultural landscape dominated by corn and soybean fields. Over a cropland region dominated by wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and grassland in Denmark, Soegaard et al. (2003) reported good agreement between CO_2 fluxes measured at 48 m and at ground level during a single growing season (June to August) based on both half-hourly and daily bases. Similarly, one-to-one direct intercomparisons of our daily CO_2 fluxes from 10 m height vs. each of our two cropped fields (data not shown) also indicated general agreement between measurements at the different heights. Additionally, certain data scattering observed in these several intercomparative analyses can also be in part attributed to natural variability of CO_2 fluxes, changes in CO_2 storage in the air column (Soegaard et al., 2003; Suyker et al., 2005; Verma et al., 2005) as well as differences in turbulence at different EC heights (Soegaard et al., 2003) and over differing surfaces (Hernandez-Ramirez et al. (2010, 2011c) [i.e., in our study means of friction velocity (m s^{-1}) were 0.29 over the soybean field, 0.33 over the corn field, and 0.34 at 10 m height (with unvarying standard errors of 0.001) during the 2006–2007 period; data not shown].

3.3. Carbon dioxide fluxes: Management effects and intra-annual variations

Further examination of cumulative CO_2 exchange by seasonal components indicated that a consistent 21 ± 1% of the carbon uptake during the growing seasons in the corn fields was emitted back to the atmosphere during the fallow periods (November through April) (Table 1). Specifically, 7 ± 2% of the carbon uptake within a given corn growing season was emitted during the succeeding fall (November and December). Interestingly, this fall-emitted CO_2 was 40% higher from our corn fields than from the adjacent soybean fields (39 ± 7 vs. 28 ± 5 g C m^{-2}; Table 1). This transient, differential CO_2 emission across cropped fields was not observed during the January through April period (83 and 78 g C m^{-2}). Increased fall CO_2 emission in corn vs. soybean fields could be explained by relatively greater residue production by corn as a substrate for microbial respiration and also by differences in tillage management across fields. As in our study, fall tillage is typically applied only during the corn years of corn–soybean

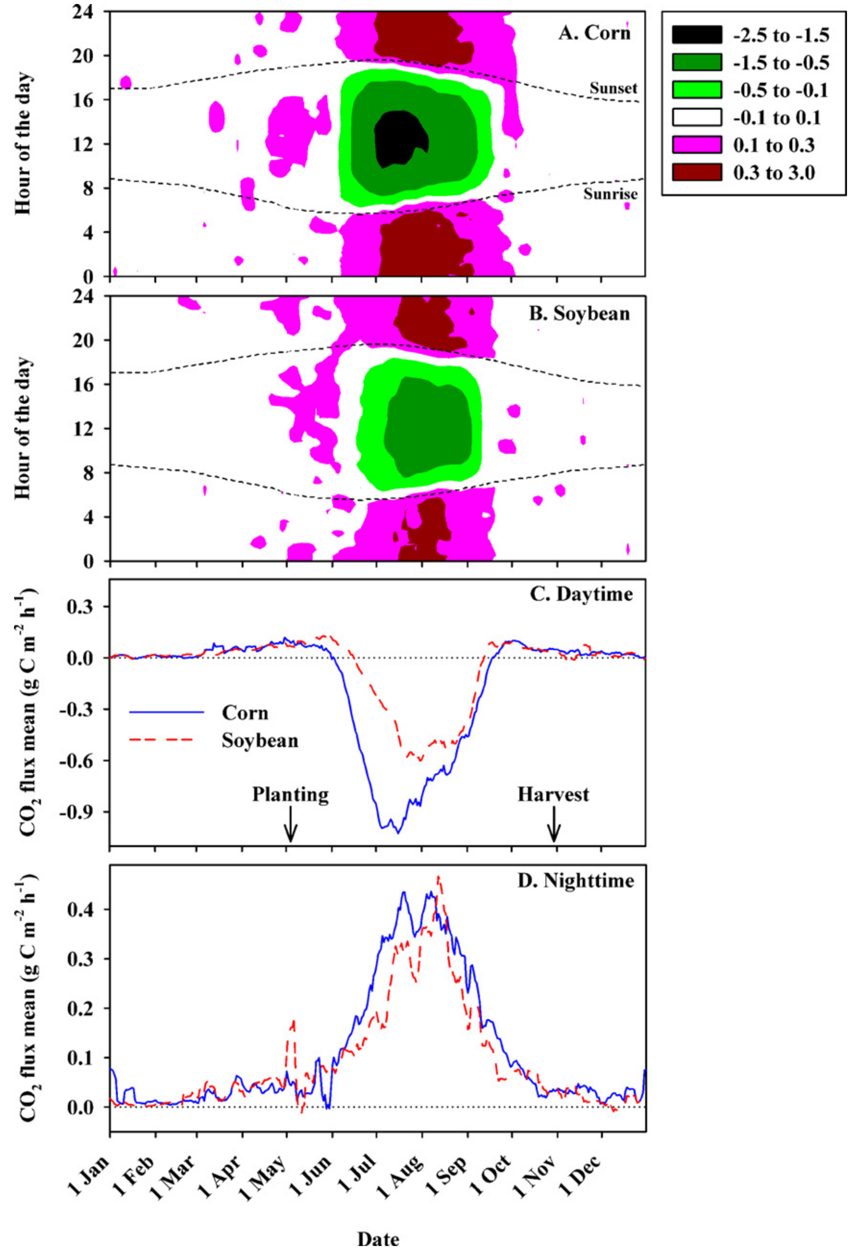

Fig. 3. Temporal dynamics of carbon dioxide (CO_2) fluxes (g C m^{-2} h^{-1}) over a corn–soybean rotation in Iowa. Diel fluctuations over (A) corn and (B) soybean fields, and (C) daytime and (D) nighttime means. Composite data from original 15-min values for 8 site-years (*n*: 189,122). Shown diel data (A and B) were averaged both hourly and over 7-day intervals. The indicated times of sunrise and sunset in panels A and B are based on on-site solar radiation measurements where daytime was defined as solar radiation greater than 100 W m^{-2}. Daily (C) daytime and (D) nighttime mean data are presented as 7-day moving averages. Note the different *y*-scales between panels C and D. Typical dates of planting and harvest are indicated. Typical date of growth stage R1 for corn was on 18 July, while R1 and R5 for soybean were on 9 July and 11 August, respectively.

rotations managed under conventional tillage (Hernandez-Ramirez et al., 2009a, 2011b), and therefore, soybean fields do not typically receive such tillage-induced soil disturbance during the fall that would stimulate short-lived CO_2 losses owing to increases in both out-gassing and respiration (Ellert and Janzen, 1999; Rochette and Angers, 1999). Our soil chamber measurements during the fall 2004 also clearly support this episodic effect of tillage on CO_2 losses by revealing 2.6 times greater surface CO_2 emission during the three weeks immediately following the fall tillage operation in mid November (Fig. 2). Moreover, during the summer of 2004 under fallow conditions (areas within the cropped fields with no plants), chamber-measured soil respiration was in general higher in soybean than in corn fields (Fig. 2); this result can also be presumably attributed to microbial decomposition of the relatively large mass of corn residue recently-added during the preceding fall.

Detailed graphical analyses of CO_2 flux dynamics across annual and diel cycles based on our 8 site-year data permitted identification of typical times for shifts between CO_2 source and sink as well as peaks of CO_2 emission and/or uptake in corn and soybean fields during daytime and/or nighttime (Fig. 3). As expected, our cropped fields registered near null to low CO_2 fluxes during most of the fallow periods for both nighttime and daytime. In further detail, during the November-to-April periods, 72% of our daily CO_2 flux observations were within the narrow range of −0.1 to +1.0 g C m^{-2} day^{-1}, while 21% of the flux values during these six-month fallow periods were above +1.0 g C m^{-2} day^{-1}. Also, certain low net CO_2 uptake values ranging from −0.1 to −1.0 g C m^{-2} day^{-1} (mean and standard error of -0.29 ± 0.04; data not shown) were sporadically observed in our study but only during 11 ± 4% of the days within the three coldest winter months (i.e., December,

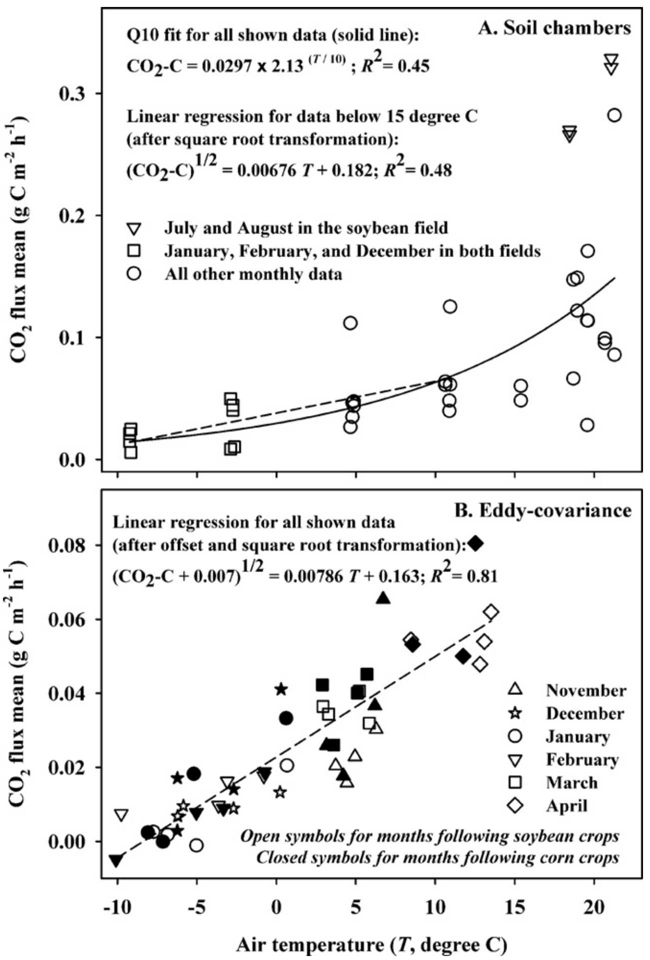

Fig. 4. Soil carbon dioxide (CO_2) fluxes dependency on air temperature under fallow conditions in corn and soybean fields. Monthly averages of CO_2 fluxes measured by (A) soil chambers (*n*: 40 chamber-months) and (B) eddy-covariance (*n*: 47 site-months) methods. Linear and Q_{10} data fits are presented. Note the different *y*-scales across panels.

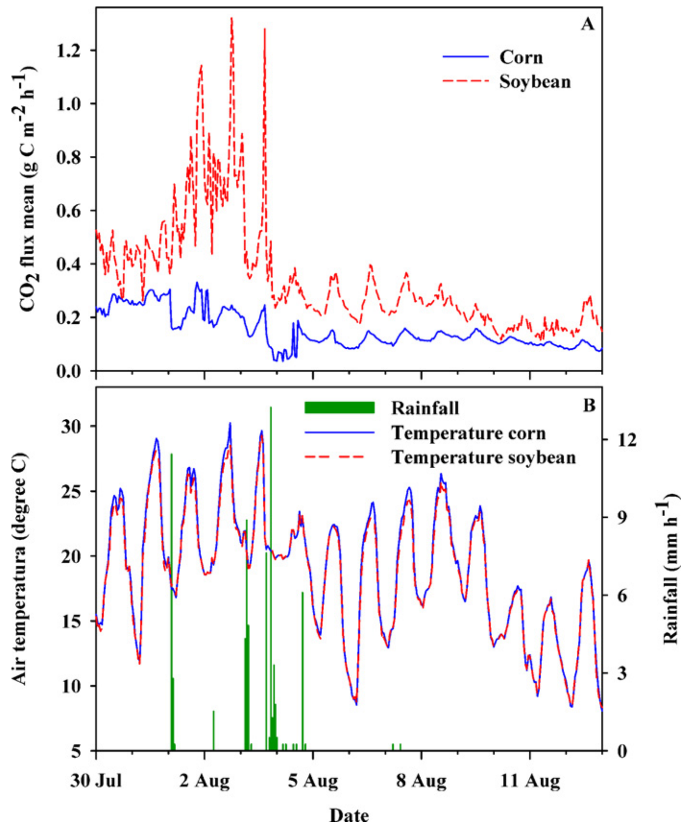

Fig. 5. Soil carbon dioxide (CO_2) fluxes and biophysical covariates under fallow conditions in corn and soybean fields during a selected interval (i.e., 30 July through 13 August 2004). (A) Hourly CO_2 flux averages, (B) air temperature means and cumulative rainfall.

January, and February with ambient temperature of $-4.4 \pm 0.7\,°C$). In contrast, the growing season (May through October) exhibited most of the observed dynamics of CO_2 fluxes. Certain diurnal and nocturnal CO_2 emissions are evident in May; both autotrophic and heterotrophic respiration can contribute to these emissions during this early growing season period as crops are established and canopies start to develop. Conversely, from June throughout September, both the photosynthesis-driven carbon uptake during the daytime (Fig. 3C) and carbon emission during the nighttime (Fig. 3D) were evident. The shifts of diurnal CO_2 exchange from source to sink for both crops took place within June. In further detail, diurnal CO_2 sink started earlier for corn than for soybean (i.e., 1 June for corn at growth stages V2 to V3 vs. 17 June for soybean at V3 to V4; Fig. 3C). The return to diurnal CO_2 source occurred roughly on 15 September for both crops as canopies are gradually senescing. Collectively, these results indicate that CO_2 sink periods were typically 106 days for corn and 90 days for soybean. In addition, the diurnal CO_2 uptake peak was stronger for corn than for soybean (-1.03 vs. $-0.60\,g\,C\,m^{-2}\,h^{-1}$), and the soybean CO_2 uptake peak occurred approximately one month later than for corn (Fig. 3C), which is consistent with phenological dissimilarities between these two crops resulting in temporal differences of maximum canopy developments (i.e., whereas R1 for corn was on 18 July, soybean R5 growth stage occurred typically on 11 August). Concomitantly, corn exhibited more diurnal CO_2 uptake in July than in August, whereas soybean showed the opposite pattern (August > July). Furthermore, the marked seasonal peak of nocturnal CO_2 emission in both fields during July to August can be directly attributed to the combination of canopy and root respiration as well as heterotrophic microbial respiration associated with increasing ambient temperatures and progressive decays of crop root systems. Collectively, these results agree with previous reports of CO_2 exchange dynamics over corn and soybean fields within the Midwestern U.S. (Suyker et al., 2004, 2005; Verma et al., 2005; Hatfield et al., 2007), and our analyses further extend these existing reports by separating the diurnal and nocturnal flux-components for both diel and annual cycles. Overall, these findings should inform modeling efforts toward enhancing predictive ability of CO_2 exchange over agricultural surfaces.

3.4. Temperature, rainfall, and light effects on CO_2 fluxes

A substantial body of literature has been established on the dependencies of CO_2 fluxes on ambient temperature, rainfall patterns, and available light; our results in general corroborate and add to the existing reports. As previously documented for forest (Law et al., 2002; Griffis et al., 2003), grazed pasture (Brown et al., 2009), and shrubland (Reverter et al., 2010) sites, our results also suggest a direct control of temperature on CO_2 fluxes under fallow conditions in cropped fields (Fig. 4). Using R^2 as a criterion, the best fits to data from both soil chambers (Fig. 4A) and eddy-covariance (Fig. 4B) were linear for air temperatures ranging from -10 to $15\,°C$, and concurrently, the corresponding regression coefficients (β_1s) for soil chambers (0.00676, Fig. 4A) and eddy-covariance data (0.00786, Fig. 4B) did not differ from each other ($P > 0.05$; β_1s were derived on transformed CO_2 flux data), indicating consistent linear

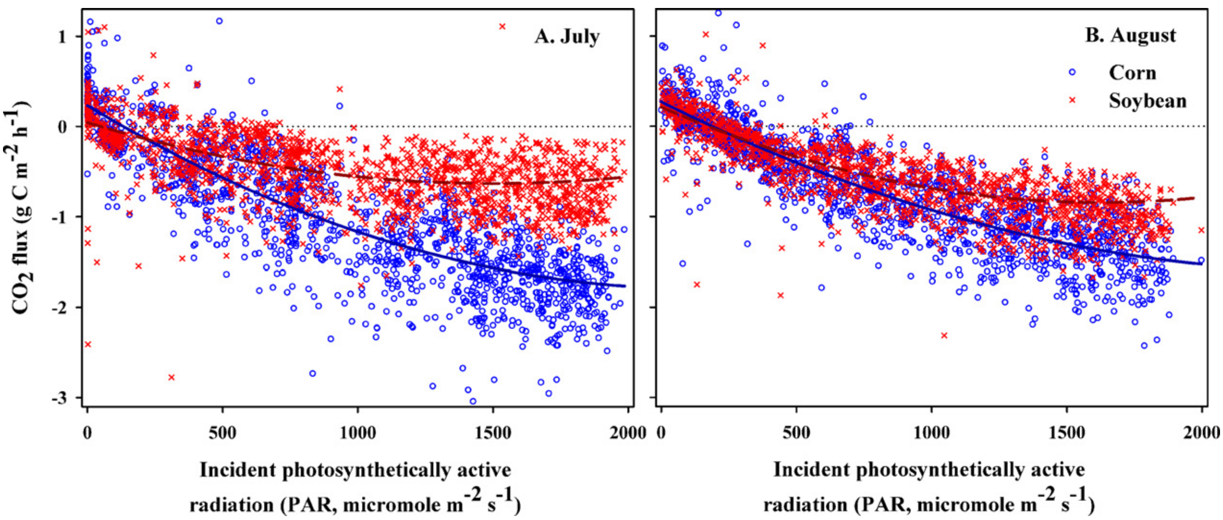

Fig. 6. Light responses of carbon dioxide (CO_2) fluxes over corn and soybean canopies during (A) July and (B) August. Shown data correspond to daytime hourly averages from 8 site-years (*n*: 5204). Shown lines correspond to polynomial data-fittings for corn (solid lines) during July (CO_2 flux = 0.0000004PAR^2 − 0.0018PAR + 0.233; R^2 = 0.73) and August (CO_2 flux = 0.0000003PAR^2 − 0.0009PAR + 0.0433; R^2 = 0.35) as well as for soybean (dash lines) during July (CO_2–C flux = 0.0000003PAR^2 − 0.0015PAR + 0.272; R^2 = 0.72) and August (CO_2–C flux = 0.0000004PAR^2 − 0.0013PAR + 0.212; R^2 = 0.65).

sensitivity of soil respiration within low temperature ranges. This finding is in clear agreement with Ginting et al. (2003) who also reported a simple linear response of soil CO_2 fluxes to soil temperature (<18 °C) during a fallow period of a continuous corn system. Furthermore, when including all our available chamber data with air temperatures from -10 to 22 °C, the best fit was Q_{10} (Fig. 4A); this pronounced curvilinear response indicates incremental sensitivity of soil respiration to higher temperatures (Parkin and Kaspar, 2003; Davidson et al., 2006). In further examination of the chamber data (Fig. 4A), Q_{10} fitting was also better than linear after excluding the extremely high monthly averages: July and August in the soybean field [CO_2–C = 0.029 × 1.94$^{(T/10)}$, R^2 = 0.56; acronyms and units as defined in Fig. 4]. Graphical analysis by diel cycles under fallow conditions during the warm summer period further supports the clear response of soil respiration to temporal fluctuations in ambient temperature (Fig. 5). Moreover, it was also found that within a period with relatively higher temperatures (31 July to 3 August 2004), soil CO_2 emission largely increased during certain days (i.e., 1, 2, and 3 August) following a major rainfall (70 mm on 1 August) (Fig. 5). However, regardless of additional major rainfalls on 3 and 4 August, soil CO_2 emission sharply decreased during the subsequent days (4–12 August) in clear association with a significant reduction in ambient temperature. These observations may suggest that synergistic effects of temperature and moisture on increased soil CO_2 emission become only evident under high temperature levels. These responses of chamber-measured soil CO_2 fluxes to environmental controls were particularly pronounced in the soybean field where a large corn-residue mass had been added in the preceding fall as discussed above.

Rainfall events also showed discernable driving effects on temporal dynamics of EC-measured ecosystem CO_2 uptake. Within two selected periods between major rainfalls [13-day (3 through 19 July 2005) and 8-day periods (24 July through 9 August 2007)], the maximum daytime mean of net CO_2 uptake over both crops were consistently observed on the third day after major rainfalls and with high incident PAR (data not shown). Also, although these assessed periods between rainfalls led to certain declines in soil water content, soil water in our field sites can in general be characterized as a non-limiting soil water availability condition (Logsdon et al., 2009, 2010) for corn and soybean growths as the minimum surface soil water content measured at our sites during the entire 4-year study was 0.15 m^3 m^{-3} (0 to 0.10 m depth; data not shown). These non-stress moisture conditions for plant growth typically occur in humid temperate regions with fine-textured soils and relatively uniform rainfall distribution (Logsdon et al., 2009, 2010) such as the Central and Eastern U.S. Corn Belt.

When plants are active growing, available light is considered a major driver of ecosystem CO_2 uptake as photosynthesis is stimulated (Suyker et al., 2004, 2005; Glenn et al., 2010). Our results support this general notion (Fig. 6). Regardless of data scattering, light response tended higher for corn than for soybean during July (Fig. 6A) when the corn canopy reached maximum development, while both corn and soybean exhibited more similar light responses during August (Fig. 6B) when the soybean canopy reached maximum development and as the demand for maintenance energy in the corn canopy gradually increases. In addition to phenological differences between crops, photosynthetic C4 physiology in corn vs. C3 in soybean (with photorespiration) can in part explain these differences in light responses across crop species and months. Nonetheless, as indicated above, most previous studies examined these effects of available light as a single factor only. Our graphical analysis of daytime hourly CO_2 fluxes as a simultaneous function of both available light (incident PAR) and air temperature (T) revealed an additive effect of these two control variables on net CO_2 uptake only for corn [Fig. 7; the resulting equation after offsetting and transforming CO_2 data was Ln (CO_2–C + 10) = 2.380–0.000108PAR–0.00282T, R^2 = 0.77]. Such combined additive effect, which resulted in notably greater CO_2 uptake, had not been previously reported in the existing literature for annual crop species. In further details, this effect was clearly evident where air temperature was above 26 °C and incident PAR in the subrange from 1400 to 1900 μmol m^{-2} s^{-1} resulting in a solid CO_2 uptake peak ranging from −1.5 to −3.0 g C m^{-2} h^{-1} (Fig. 7). Overall, incident PAR and air temperature explained 74% and 3%, respectively, of the total variability in the data, and this temperature contribution to this additive response model was mostly noticeable with temperatures higher than 23 °C. As a biological process, increased photosynthesis, and hence ecosystem CO_2 uptake, depends on available light as a direct energy input and on air temperature as a scalar expression of ambient heat and thermodynamic driver of photosynthetic and respiratory activities. In general, as observed in our study, these responses to temperature and available light can be expected to be even more pronounced in C4 than in C3 plants (Taiz and Zeiger, 2002).

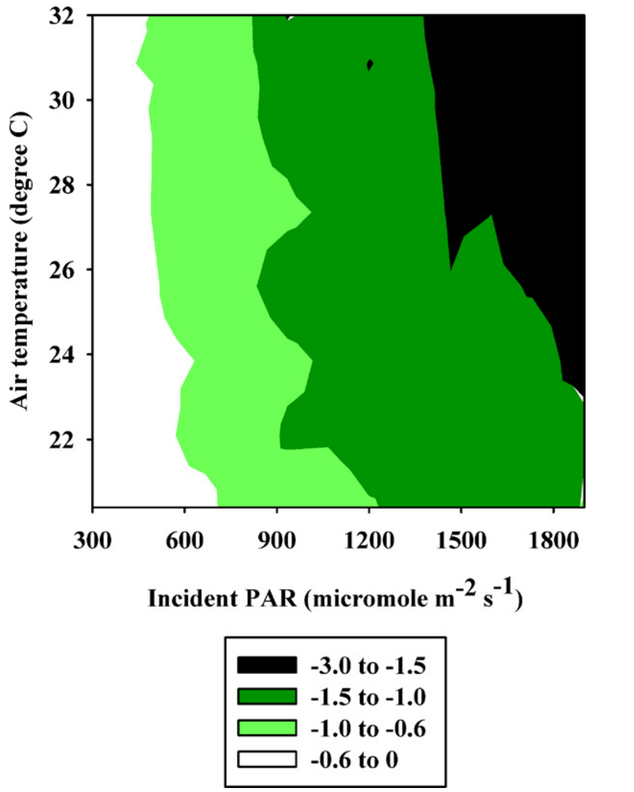

Fig. 7. Carbon dioxide (CO_2) fluxes ($g\,C\,m^{-2}\,h^{-1}$) over corn canopies as a simultaneous function of both incident photosynthetically active radiation (PAR) density and air temperature. Data correspond to hourly averages during the daytime of July and August from 4 site-years. Measured CO_2 fluxes were smoothed using an inverse distance function with a power of 2 and a sampling proportion of 10% of nearest neighbours. *n*: 2977.

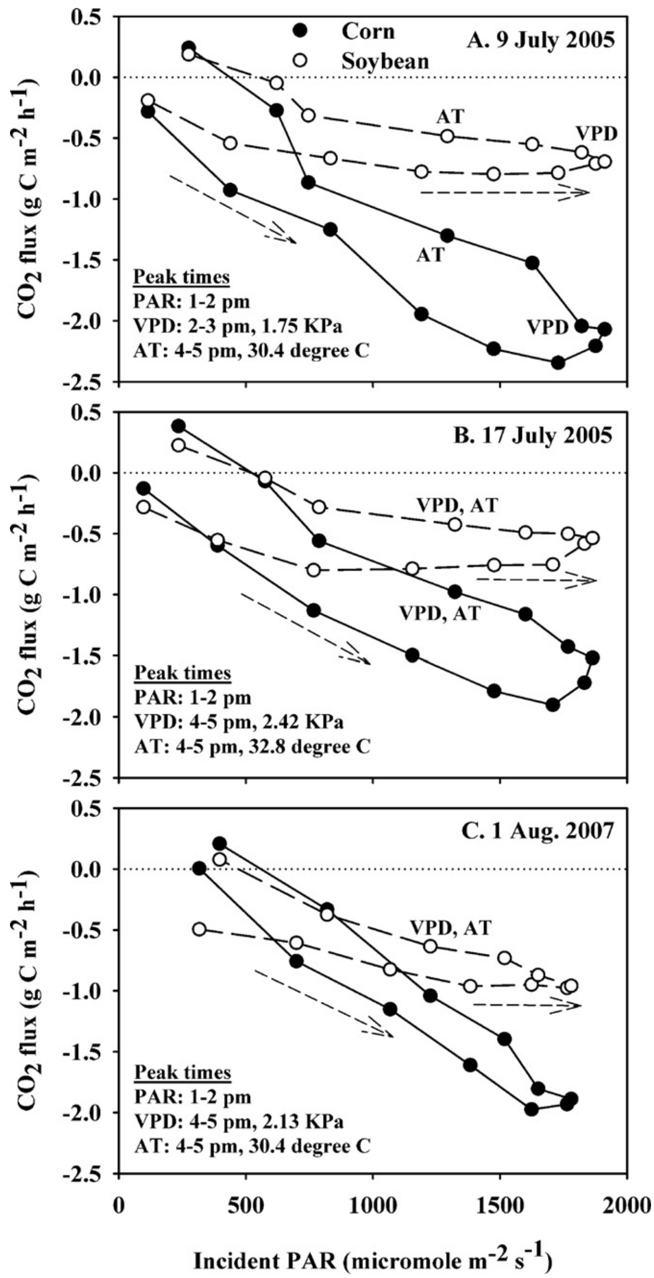

Fig. 8. Light responses of carbon dioxide (CO_2) flux over corn and soybean canopies during three clear days [i.e., (A) 9 and (B) 17 July 2005, and (C) 1 August 2007). The CO_2 flux and incident photosynthetically active radiation (PAR) density data are presented as hourly averages. Arrows indicate the directions of the diurnal time courses. Peak times of PAR, vapor pressure deficit (VPD), and air temperature (AT) are provided along with their corresponding maximum diurnal values.

3.5. Diurnal hysteresis of ecosystem CO_2 uptake

Results revealed pronounced diurnal hystereses in the light response curves over both crops that can be attributed to delay in the diurnal peak of soil CO_2 respiration relative to the time of maximum plant photosynthesis (Fig. 8). Under our non-limiting soil water conditions as discussed above, systematically lower ecosystem CO_2 uptake in the afternoons than in the mornings for any given PAR level can be directly attributed to relatively increased CO_2 respiratory losses from soil and roots in late afternoon when higher ambient and soil temperature also occur. In other words, photosynthetic activity would typically follow incident PAR (Taiz and Zeiger, 2002), while soil respiration would track the diel patterns of ambient temperature as demonstrated after a comprehensive analysis of soil CO_2 fluxes by Parkin and Kaspar (2003) and also in our chamber data (Fig. 5). This delay between the diurnal peaks of incident PAR and air temperature was roughly 3 h (Fig. 8), and hence, the observed differential response of CO_2 exchange between mornings vs. afternoons. The amplitude of this hysteresis between mid mornings and mid afternoons was roughly two-fold larger for corn than for soybean (0.59 ± 0.11 vs. $0.32 \pm 0.03\,g\,C\,m^{-2}\,h^{-1}$; Fig. 8). These observed diurnal hysteretic responses of CO_2 exchange had not been well documented over corn and soybean canopies. Recently, both Pingintha et al. (2010) and Reverter et al. (2010) also described hystereses of net CO_2 uptake over non-irrigated peanut (*Arachis hypogaea* L.) and alpine shrubland, respectively. Reverter et al. (2010) attributed in part these diurnal path dependencies to sugar accumulation in leaves in the afternoon after intensive photosynthesis in the morning which could decrease Rubisco activity, particularly in C3 plants such as soybean. Furthermore, under plant water stress conditions due to drought, both Pingintha et al. (2010) and Reverter et al. (2010) observed even more amplified hysteretic responses of daytime net CO_2 uptake to PAR. Specifically, they found these effects in fields with soil water content below 0.04 (Pingintha et al., 2010) and 0.08 $m^3\,m^{-3}$ (Reverter et al., 2010), and in clear association with high VPD values during the midday and afternoon which could sharply restrict stomatal conductance, and hence, considerably reduce plant CO_2 uptake, in particular in C3 plants. However, these divergent effects of high VPD on CO_2 uptake-PAR hystereses were not observed under non-limiting water conditions (Pingintha et al., 2010; Reverter et al., 2010). These findings are consistent with results in our corn and soybean fields (Fig. 8) where non-limiting soil water conditions were predominant; thus, increased VPD did not appear to have additional major influence on our described hysteretic courses of ecosystem CO_2 uptake (Fig. 8). Nonetheless, these overall observed diurnal hystereses of ecosystem CO_2 uptake need to be reexamined using absorbed PAR and leaf photosynthesis measurements under a broader variety of canopy conditions. Collectively, these findings can contribute in part to explain the scattering observed in light response curves (Fig. 6), and they should inform modeling efforts as well as aid to develop more robust data gap-filling procedures.

4. Conclusion

This multiyear study identified wide variations in CO_2 fluxes as a function of environmental factors including available light, ambient temperature, and rainfall patterns. Ambient temperature explained a large portion of the observed variability in soil CO_2 emission under field fallow conditions. When corn and soybean canopies were photosynthetically active and behaving as CO_2 sinks, fluctuation in available light was the single more important driver of CO_2 uptake followed by ambient temperature in these annual cropping systems where water supply is not typically limiting. Moreover, this study found clear hysteresis of diurnal CO_2 uptake as a function of available light with greater net CO_2 uptake during mornings than afternoons over both crop canopies. Also, this study indicates good agreement between CO_2 exchange measurements done directly over these two adjacent agricultural fields (simple average of the CO_2 exchange for the assessed corn–soybean rotation) compared with quantification at regional footprint scale level (10 m height over the ground). Additionally, results suggest that crop species and phenologies affect the length of the CO_2 sink periods, peak rates of CO_2 uptake, and time of peak uptake within growing seasons. Sink periods were typically two weeks longer for corn than for soybean, and peak uptake happened two to three weeks earlier for corn than for soybean. Annual cumulative CO_2 exchanges ($g\,C\,m^{-2}\,year^{-1}$) were -466 ± 38 for corn and -13 ± 39 for soybean. Based on these results and estimated carbon balance, soybean appears to induce depletion of soil carbon, while corn seems to be carbon neutral. Changes in land use and crop management can largely impact exchange of CO_2 from agricultural regions.

Acknowledgments

We sincerely thank Timothy Hart, Otis B. Smith, and Forrest E. Goodman for installing and maintaining the field instrumentations; their dedicated, continuous technical work made this study possible. Also, to Steve and Barb Kaltenheuser for facilitating the implementation of this study on their farm.

References

Amiro, B., 2010. Estimating annual carbon dioxide eddy fluxes using open-path analysers for cold forest sites. Agric. For. Meteorol. 150, 1366–1372.
Baker, J.M., Griffis, T.J., 2005. Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. Agric. For. Meteorol. 128, 163–177.
Brown, M., Whitehead, D., Hunt, J.E., Clough, T.J., Arnold, G.C., Baisden, W.T., Sherlock, R.R., 2009. Regulation of soil surface respiration in a grazed pasture in New Zealand. Agric. For. Meteorol. 149, 205–213.
Davidson, E.A., Janssens, I.A., Luo, Y.Q., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q(10). Global Change Biol. 12, 154–164.
Ellert, B.H., Janzen, H.H., 1999. Short-term influence of tillage on CO_2 fluxes from a semi-arid soil on the Canadian prairies. Soil Tillage Res. 50, 21–32.
Ginting, D., Kessavalou, A., Eghball, B., Doran, J.W., 2003. Greenhouse gas emissions and soil indicators four years after manure and compost applications. J. Environ. Qual. 32, 23–32.
Glenn, A.J., Amiro, B.D., Tenuta, M., Stewart, S.E., Wagner-Riddle, C., 2010. Carbon dioxide exchange in a northern prairie cropping system over three years. Agric. For. Meteorol. 150, 908–918.
Granier, A., Reichstein, M., Breda, N., Janssens, I.A., Falge, E., Ciais, P., Grunwald, T., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Kostner, B., Lagergren, F., Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, T., Wang, Q., 2007. Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. Agric. For. Meteorol. 143, 123–145.
Grant, R.F., Arkebauer, T.J., Dobermann, A., Hubbard, K.G., Schimelfenig, T.T., Suyker, A.E., Verma, S.B., Walters, D.T., 2007. Net biome productivity of irrigated and rainfed maize–soybean rotations: modeling vs. measurements. Agron. J. 99, 1404–1423.
Graßl, H., 2009. Scenarios of climate change. Eur. Phys. J. Special Topics 176, 5–12.
Grelle, A., Burba, G.G., 2007. Fine-wire thermometer to correct CO_2 fluxes by open-path analyzers for artificial density fluctuations. Agric. For. Meteorol. 147, 48–57.
Griffis, T.J., Black, T.A., Morgenstern, K., Barr, A.G., Nesic, Z., Drewitt, G.B., Gaumont-Guay, D., McCaughey, J.H., 2003. Ecophysiological controls on the carbon balances of three southern boreal forests. Agric. For. Meteorol. 117, 53–71.
Hatfield, J.L., Prueger, J.H., Kustas, W.P., 2007. Spatial and temporal variation of energy and carbon fluxes in central Iowa. Agron. J. 99, 285–296.
Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scoyoc, G.E., 2009a. Carbon and nitrogen dynamics in an eastern corn belt soil: N source and rotation. Soil Sci. Soc. Am. J. 73, 128–137.
Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scoyoc, G.E., 2009b. Greenhouse gas fluxes in an eastern Corn Belt soil: weather, nitrogen source and rotation. J. Environ. Qual. 38, 841–854.
Hernandez-Ramirez, G., Hatfield, J.L., Prueger, J.H., Sauer, T.J., 2010. Energy balance and turbulent flux partitioning in a corn–soybean rotation in the midwestern U.S. Theor. Appl. Climatol. 100, 79–92.
Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scoyoc, G.E., 2011a. Nitrogen partitioning and utilization in corn cropping systems: rotation, N source, and N timing. Eur. J. Agron. 34, 190–195.
Hernandez-Ramirez, G., Sauer, T.J., Cambardella, C.A., Brandle, J.R., James, D.E., 2011b. Carbon sources and dynamics in afforested and cultivated corn belt soils. Soil Sci. Soc. Am. J. 75, 216–225.
Hernandez-Ramirez, G., Sauer, T.J., Hatfield, J.L., Prueger, J.H., 2011c. Quantifying atmospheric stability conditions at a swine facility and an adjacent corn field in Iowa, USA. Theor. Appl. Climatol. doi:10.1007/s00704.011. 0405-0.
Hollinger, S.E., Bernacchi, C.J., Meyers, T.P., 2005. Carbon budget of mature no-till ecosystem in north central region of the United States. Agric. For. Meteorol. 130, 59–69.
Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. Tellus 51B, 298–313.
Huggins, D.R., Allmaras, R.R., Clapp, C.E., Lamb, J.A., Randall, G.W., 2007. Corn–soybean sequence and tillage effects on soil carbon dynamics and storage. Soil Sci. Soc. Am. J. 71, 145–154.
Hutchinson, G.L., Mosier, A.R., 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45, 311–316.
Hutchinson, J.J., Campbell, C.A., Desjardins, R.L., 2007. Some perspectives on carbon sequestration in agriculture. Agric. For. Meteorol. 142, 288–302.
IPCC (Intergovernmental Panel on Climate Change), 2007. Climate change 2007: the physical science basis. In: Contribution of Working Group I to the 4th Assessment Rep. (AR4) of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.
Jaksic, V., Kiely, G., Albertson, J., Oren, R., Katul, G., Leahy, P., Byrne, K.A., 2006. Net ecosystem exchange of grassland in contrasting wet and dry years. Agric. For. Meteorol. 139, 323–334.
Johnson, J.M.F., Reicosky, D.C., Allmaras, R.R., Sauer, T.J., Venterea, R.T., Dell, C.J., 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Tillage Res. 83, 73–94.
Law, B.E., Falge, E., Gu, L., Baldocchi, D.D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A.J., Falk, M., Fuentes, J.D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I.A., Jarvis, P., Jensen, N.O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, U.K.T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agric. For. Meteorol. 113, 97–120.
Logsdon, S.D., Hernandez-Ramirez, G., Hatfield, J.L., Sauer, T.J., Prueger, J.H., Schilling, K.E., 2009. Soil water and shallow groundwater relations in an agricultural hillslope. Soil Sci. Soc. Am. J. 73, 1461–1468.
Logsdon, S.D., Sauer, T.J., Hernandez-Ramirez, G., Hatfield, J.L., Kaleita-Forbes, A., Prueger, J.H., 2010. Effect of corn or soybean row position on soil water. Soil Sci. 175, 530–534.
Migliavacca, M., Reichstein, M., Richardson, A.D., Colombo, R., Sutton, M.A., Lasslop, G., Tomelleri, E., Wohlfahrt, G., Carvalhais, N., Cescatti, A., Mahecha, M.D., Montagnani, L., Papale, D., Zaehle, S., Arain, A., Arneth, A., Black, T.A., Carrara, A., Dore, S., Gianelle, D., Helfter, D., Hollinger, D., Kutsch, W.L., Lafleur, P.M., Nouvellon, Y., Rebmann, C., da Rocha, H.R., Rodeghiero, M., Roupsard, O., Sebastia, M.T., Seufert, G., Soussana, J.-F., van der Molen, M.K., 2011. Semiempirical modeling of abiotic and biotic factors controlling ecosystem respiration across eddy covariance sites. Global Change Biol. 17, 390–409.
Parkin, T.B., Kaspar, T.C., 2003. Temperature controls on diurnal carbon dioxide flux: implications for estimating soil carbon loss. Soil Sci. Soc. Am. J. 67, 1763–1772.
Pereira, J.S., Mateus, J.A., Aires, L.M., Pita, G., Pio, C., David, J.S., Andrade, V., Banza, J., David, T.S., Paco, T.A., Rodrigues, A., 2007. Net ecosystem carbon exchange in three contrasting Mediterranean ecosystems–the effect of drought. Biogeosciences 4, 791–802.

Pingintha, N., Leclerc, M.Y., Beasley Jr., J.P., Durden, D., Zhang, G., Senthong, C., Rowland, D., 2010. Hysteresis response of daytime net ecosystem exchange during drought. Biogeosciences 7, 1159–1170.
Reverter, B.R., Sanchez-Canete, E.P., Resco, V., Serrano-Ortiz, P., Oyonarte, C., Kowalski, A.S., 2010. Analyzing the major drivers of NEE in a Mediterranean alpine shrubland. Biogeosciences 7, 2601–2611.
Reverter, B.R., Carrara, A., Fernández, A., Gimeno, C., Sanz, M.J., Serrano-Ortiz, P., Sánchez-Canete, E.P., Were, A., Domingod, F., Resco, V., Burba, G.G., Kowalski, A.S., 2011. Adjustment of annual NEE and ET for the open-path IRGA self-heating correction: magnitude and approximation over a range of climate. Agric Forest Meteorol 151, 1856–1861.
Rochette, P., Angers, D.A., 1999. Soil surface carbon dioxide fluxes induced by spring, summer, and fall moldboard plowing in a sandy loam. Soil Sci. Soc. Am. J. 63, 621–628.
Russell, E., Laird, D.A., Parkin, T.B., Mallarino, A.P., 2005. Impact of nitrogen fertilization and cropping system on carbon sequestration in midwestern mollisols. Soil Sci. Soc. Am. J. 69, 413–422.
Saito, M., Kato, T., Tang, Y., 2009. Temperature controls ecosystem CO_2 exchange of an alpine meadow on the northeastern Tibetan Plateau. Global Change Biol. 15, 221–228.
Sauer, T.J., Singer, J.W., Prueger, J.H., Desutter, T.M., Hatfield, J.L., 2007. Radiation balance and evaporation partitioning in a narrow-row soybean canopy. Agric. Forest Meteorol. 145, 206–214.
Soegaard, H., Jensen, N.O., Boegh, E., Hasager, C.B., Schelde, K., Thomsen, A., 2003. Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modeling. Agric. For. Meteorol. 114, 153–173.
Suyker, A.E., Verma, S., Burba, G., Arkebauer, T.J., 2005. Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season. Agric. For. Meteorol. 131, 180–190.
Suyker, A.E., Verma, S.B., Burba, G.G., Arkebauer, T.J., Walters, D.T., Hubbard, K.G., 2004. Growing season carbon dioxide exchange in irrigated and rainfed maize. Agric. For. Meteorol. 124, 1–13.
Taiz, L., Zeiger, E., 2002. Plant Physiology, third edn. Sinauer Associates, Sunderland, MA.
Unger, S., Maguas, C., Pereira, J.S., Aires, L.M., David, T.S., Werner, C., 2010. Disentangling drought-induced variation in ecosystem and soil respiration using stable carbon isotopes. Oecologia 163, 1043–1057.
Verma, S.B., Dobermann, A., Cassman, K.G., Walters, D.T., Knops, J.M., Arkebauer, T.J., Suyker, A.E., Burba, G.G., Amos, B., Yang, H., Ginting, D., Hubbard, J.G., Gitelson, A.A., Walter-Shea, E.A., 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agric. For. Meteorol. 131, 77–96.
Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quart. J. Roy. Meteorol. Soc. 106, 85–100.